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THE DEVELOPMENT OF FUEL CELL TECHNOLOGY AND SUGGESTIONS CONCERNING DEVELOPMENT OF THESE TECHNIQUES IN CHINA

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ABSTRACT This article introduces the newest developments in several important models of fuel cell. Based on world development trends and the concrete situation in China, the author has put forward corresponding policies for the areas of alkaline fuel cells, phosphorous acid fuel cells, molten carbonate cells, and polymer electrolyte fuel cells in order to promote research and development associated with Chinese fuel cells.

KEY WORDS Fuel Cell, Alkaline Fuel Cell, Phosphorous Acid Fuel Cell, Molten Carbonate Fuel Cell, Polymer Electrolyte Fuel Cell

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* Numbers in margins indicate foreign pagination. Commas in numbers indicate decimals.

Development of relevant fuel cell technologies in recent years can be referred to in references [1-9]. Summarizing, the situation is as follows:

(1) 10kW level high performance alkaline fuel cell (AFC) sets have already become the primary electric power source for the U.S. space shuttle. Up to now, they have already been applied over the last 20 years and have been proven safe and reliable. Cell sets, at a minimum, are capable of operating for 2500 hours without needing maintenance. The European Hermes space ferry plan has already decided to opt for the use of AFC as electric power source. Responsibility for development was accepted by Germany's Siemens AG , and use is projected in the later 1990's on the maiden voyage of the space ferry. However, due to the expensive construction cost of this type of system, in conjunction with it, liquid hydrogen has been used as fuel. Therefore, ground use is not suitable. Early attempts at taking AFC and using them in powering vehicles and submarines have already been discontinued.

(2) Megawatt level phosphorous acid fuel cell (PAFC) technology is already basically mature. At the present time, it is in the early stages of product commercialization. A series of 50kW - 11MW PAFC cells have already gone through or are in the midst of trial operation. Up to now, test results are good. Power station operating energies basically satisfy design requirements. For example, Japan's Tokyo Electric Power Company has already completed test runs of 4.5MW water cooled PAFC power stations [built by the U.S. United Technology Company (UTC)] (April 1983 - December 1985. Total of 2423 operating hours. 5430MWH of electricity generated. Efficiency 37.8%.), test runs of air cooled 220kW PAFC power stations (Built by Sanyo. Efficiency 35%.) (September 1987 - October 1989.),

as well as test runs of water cooled 220kW power stations (Built by the U.S. fuel cell company (IFC). Efficiency 37%.) (November 1988 - November 1990.), and is in the midst of carrying out test runs on 11MW PAFC power stations (Built in cooperation by the U.S. IFC and Japan's Toshiba. Efficiency 42.9%.) (Began March 1991. Planned completion March 1993.). Besides this, in Italy, there is a 1MW PAFC power station (Built by U.S IFC.) and put on test runs in early 1992. There are 4 25kW power stations (Built by Japan's Fuji. Holland's KTI supplied readjustment devices and engineering systems.) that will carry out tests in Holland and Italy. Japan's Fuji will also sell Spain, Sweden, and Italy 4 50kW PAFC power stations. The U.S. IFC will also supply 4 200kW electric power stations in Sweden, Denmark, and Germany, and do test runs. According to the assertions of the U.S. IFC, in early 1991, they had already received orders for 53 200kW power stations (mainly coming from Europe, Japan, and the U.S.). Beginning 1992-1993, they will supply the orders one after the other. It can be seen that development in this area is quite brisk. However, at the present time, it is still in the early test run phase for power plants on levels from a few thousand watts to megawatts. There is still a lack of long term (a few years) data and experience associated with continuous operation. As a result, it is estimated that it will at least be the end of this century before it is possible to take the first steps toward making them practical commercial products. It must be pointed out that, due to limited numbers of sales and there being no way to form large production capabilities, as a result, at the present time, PAFC costs are quite high ($3500/kW). This is not only far higher than the construction costs of large scale modern power plants internationally ($800-1300/kW calculated in all cases on 1991 U.S. dollar values. The same below.). It is also

higher than the estimated costs of molten carbonate fuel cell power stations (MCFC) (approximately $1500/kW).

(3) In recent years, MCFC has been just in the midst of developing from 10-20kW to megawatt levels. With internal type readjustment, MCFC also has a new breakthrough. /39

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Born 1925. Graduated Chemistry Dept. Wuhan University 1950. 1957 - 1959, engaged in advanced studies in the Chemistry Dept. of Moscow University. Currently professor Chemistry Dept. Wuhan University. 1980, selected as Chemistry section committee member of Academia Sinica. Main works include "Treatise on the Dynamics of Electrode Processes" (1976, 1987) as well as approximately 200 hundred articles published in scholarly publications inside China and abroad.

The U.S. Energy Research Corporation (ERC), beginning in 1980, has developed right along internal readjustment type MCFC using natural gas as fuel (it is planned to go a step further and use coal gas). 7kW cells have already completed tests (October 1990 - May 1991). 20kW cell sets have also already been put into testing. In conjunction with this, there are plans to expand to 100kW around 1992. What is especially worthy of attention is that, in 1991, the corporation in question signed agreements with 22 power companies to jointly support the commercial development of 2MW MCFC power stations. ERC will, on the foundation of completed 100kW cell sets, first build two 2MW demonstration

power stations. Test runs will be carried out in 1994 - 1996. After that, 50 2MW power stations will then be produced (efficiencies 57% - 60%). Initial users must pay relatively high costs (estimated at approximately $1500/kW). However, it is possible that there will be compensations obtained in profits from future sales. The ultimate sales price for 2MW power stations is estimated at between $750 - 950/kW. In 1991, the ERC already set up the Fuel Cell Engineering Corp. as well as the Fuel Cell Manufacturing Corp. There is an annual production capability for 2MW cell sets. In conjunction with this, there are plans to expand to an annual production of 5MW [10].

At the same time as this, the Molten Carbonate (M-C) Power Corp. established by the Coal Gas Technology Research Institute (IGT, U.S.) already possesses an annual production capability of 3MW cell sets (capable of expansion to 12MW/year). The corporation in question has already completed operational tests on 8kW cell sets (MCP-2). In conjunction with this, 250kW cell set test runs will be done in 1993 (MCP-3). In 1995, the corporation in question plans to receive orders for 500kW - 3MW power stations with delivery beginning in 1997. This plan has received support from the U.S. Energy Department, the state of Illinois, as well as a group of power companies and research institutes [11].

In 1989, Japan completed tests on 25kW MCFC cell sets (built by Hitachi). They had the largest powers among the MCFC cell sets already put into testing. In 1993, Japan also plans to complete test manufacture of 100kW cell sets and auxiliary equipment, and, in conjunction with this, complete the test manufacture of 1MW electric power stations. With regard to internally adjusted MCFC, 3kW cell set tests were already completed in 1989. In 1992, there are plans to

develop 30kW systems. However, speaking in general terms, Japan's development of MCFC is relatively conservative. It is certainly not optimistic that it can enter the marketplace before the end of this century [12].

(4) Polymer electrolyte membrane fuel cells (PEMFC) were originally developed in cooperation between the U.S. NASA and GE. In conjunction with that, they were successfully used in 7 Gemini flights. However, due to opting for the use of ion exchange membranes with inadequate oxidation resistance capabilities, cell set operating life was only approximately 500 hours. Beginning in the middle 1960's, GE changed to the use of full fluorine sulphonic acid membranes (Nation). Laboratory life exceeded 57,000 hours. In conjunction with this, they were utilized in biosatellite launches in 1968. However, after that, alkaline fuel cells were selected for use as manned space flight power sources, leading to a standstill in the development of polymer electrolyte membrane fuel cells for the last 20 years.

Beginning in 1983, Canada's Ballard Power System company received a commission from Canada's ministry of defense to develop PEMFC for military and civilian uses. Initially, they also opted for the use of Nation membranes. Later, they discovered that results were better using ion exchange membranes manufactured by the Dow company which were even thinner and had smaller equivalent weights [13]. At the present time, Ballard is primarily developing 3 - 5kW cell sets (35 single cells in series [electrode area $36in^2$ ($232.3cm^2$)]). Cell set dimensions are 10in x 10in x 18in (25.5 cm x 25.4cm x 45.7cm). They have already been tested for 2000 hours. There were no deterioration phenomena. On this foundation, they are in the midst of developing application research on two PEMFC. One is a 105kW cell set used as power for 16 seat transportation vehicles. Test

runs are planned in 1993. One is a PEMPC system using methyl alcohol as fuel (a further step is to use natural gas) [14].

Germany's Siemens company did studies on AFC used as submarine power. 100kW alkaline fuel cells went through testing on U-1 model submarines. At the present time, this area of interest is also turning to PEMFC. 20kW cell sets composed of 42 individual cells are just in the midst of development [15].

The advantages of PEMFC are fast start up at normal temperatures (at room temperature, it is possible to start up in 5 seconds) as well as operational reliability (the Siemens company did a test of cell operation at 0.54 Amp/cm^2 approaching 20 thousand hours). The disadvantages, by contrast, are high material costs (membranes, precious metal catalysts, and so on) as well as only being able to use high purity hydrogen as fuel. At the present time, in PEMFC, the amounts of platinum used generally exceed 4-5$mgPt/cm^2$. However, laboratory results clearly show that it is possible to drop that below 1mg/cm^2 [16,17]. At room temperature, CO has an intense toxifying effect on platinum catalysts. However, research results also clearly show that these effects, coming primarily from competitive absorption of CO and H_2, are reversible, that is, after catalyst poisoning, it is only necessary to use high purity hydrogen to treat them, and it is possible to restore activity.

(5) Direct methyl alcohol fuel cells went through in depth study in the 1970's. By the 1980's, there was a gradual tendency toward standstill. This is primarily due to very great difficulties involving catalyst problems when methyl alcohol is directly and completely oxidized on electrodes. In recent years, applications of methyl alcohol fuel cells

have already primarily opted for the use of indirect systems where hydrogen is readjusted first and then oxidized in cells. One direction which is worthy of attention is that the U.S. Energy Department has used 5 million U.S. dollars to support unified research by Case Western Reserve and few other universities on internal readjustment type methyl alcohol fuel cells. The central content is to develop proton conductor membranes capable of operating around 300øC. At the present time, this work still belongs to exploratory basic research.

(6) Solid oxide fuel cells (SOFC) still have not been turned into commercial products. However, the U.S., Western Europe, and Japan all are continuing research. The U.S. Westinghouse company is in the leading position. The 3kW electric generating equipment it manufactures has already operated for 5300 hours. In conjunction with this, it plans to manufacture and test 20kW cell sets.

According to the development status's of the various type models of fuel cell above as well as their strong and weak points, it is possible to make the estimates below about the near term application prospects of fuel cells:

(1) AFC will continue in use as the primary electric power source for manned spacecraft. In the aerospace plans of the U.S. and western Europe, in both cases, they take it as primary. This is due to the fact that AFC systems which opt for the use of liquid hydrogen (or hydrogen slurry) as fuel possess the highest weight to energy ratios and energy transformation efficiencies.

(2) As far as main power stations with powers of several tens of MW and up are concerned, in the

near term, are not capable of opting for the use of fuel cells to generate electricity. At the present time, generating turbine combined cycles (GTCC) efficiencies have already reached 44%. By the end of this century, it is estimated that it will be possible to raise this to 55%. Costs are between $900-1300/kW which, in all cases, is clearly better than PAFC. After going through selective catalyzation and original (SCR) processing, the amount of NO_2 contained can be controlled 10-20ppm. Other large scale electric generating technologies using coal as fuel, which are just in the midst of development--such as supercritical fine coal dust electric generating technology, electric generating technology associated with the pressure liquification of bed coal and conversion to gas, and so on--have electric generating efficiencies which are capable of reaching 37-39% before the end of this century. Moreover, manufacturing costs are lower than PAFC.

With regard to opting for the use of MCFC--in particular, internally readjusted types of MCFC--it carries with it the possibility of higher efficiencies than thermal power stations. Manufacturing costs are certainly not high (see above). However, at the present time, the powers associated with internally readjusted MCFC systems which have already gone through test runs, in all cases, do not exceed approximately 10kW. This is more than 4 orders of magnitude different from the power requirements of main power stations. Opting for the use of MCFC to act as a method of large scale electric generation may possibly

have to be after the 20's and 30's decades of the next century.

(3) In the near term, there is a possibility of putting into actual use fuel cell systems on the ground. Estimates are between 50kW - 10MW from dispersed model PAFC power stations. Technology for manufacturing megawatt level PAFC is already mature. Moreover, construction costs are higher for this type and scale of thermal power electric generating station. Efficiencies are generally lower than 30%-35%. Thus, PAFC power stations have a definite superiority. At the present time, the primary difficulty associated with the spread of PAFC lies in persistently high manufacturing costs for small batches. Moreover, there is also a shortage of huge investments required to create large scale production capabilities. If it is possible to get around the initial investment difficulty, it is estimated that PAFC power stations have the possibility of preliminary conversion to commercial products before the end of this century- -for example, reaching production levels of 1000MW a year or even higher.

(4) Utilizing fuel cells to act as power for transportation devices (particularly, small buses) has been a development direction very attractive to people right along. Due to the fact that transportation device motive powers are not large, it is advantageous to opt for the use of fuel cells from the angle of energy transformation efficiencies. Considered from the angle of reducing environmental pollution, fuel cells are then even more clearly superior. However, the

start up times of all fuel cell systems associated with operating temperatures higher than ambient temperatures (for example, PAFC, MCFC, and so on) are quite long in all cases. As a result, most are only suitable for use in transportation vehicles with long periods of continuous driving. On the other hand, fuel cell systems capable of starting up relatively quickly at room temperature (for example, AFC and PEMFC) also require using high purity H_2 as fuel and opting for the use of expensive materials (precious metal catalysts, special types of membrane, and so on). Before resolving these technical difficulties, fuel cell vehicles will certainly not be more attractive to people than secondary cells (particularly, new model high energy secondary cells). However, the scale of the vehicle industry is huge. At the present time, environmental pollution produced by vehicles is severe.

Developing fuel cell vehicles (acting as one constituent part of the plan to develop battery vehicles) still receives quite serious attention. As a result, one still should not underestimate the possibility of achieving important breakthroughs within a few years. Breakthroughs estimated as most possible come from the two areas below. /41

If the hydrogen storage capability of hydrogen storage materials reaches 3%-5% of hydrogen storage container weight (at the present time it is approximately 1.5%), volume as compared to energy will also increase correspondingly. Then, opting for the use of PEMFC to be the power for vehicles can possibly make a relatively quick introduction into test use. If small scale vehicle mounted pure hydrogen (mainly contains low amounts of CO) generators using methyl

alcohol or hydrocarbons as fuel can have breakthrough type developments, it is also possible to promote the early introduction of fuel cell vehicles into practical utilization. In order to shorten start up times, it is possible to install small hydrogen storage containers and secondary cells.

The start of Chinese fuel cell research and development certainly cannot be considered early. The difference between levels in the early 1970's and international levels at that time was certainly not great. However, due to lack of long term planning and sustained engagement, beginning from the middle 1970's, there was a gradual tendency toward standstill in work relating to fuel cell research and development. In this period of the last 20 years, besides a few people at the Academia Sinica's Dalian Chemistry and Physics Institute persistently continuing to engage in work relating to fuel cells, a nation wide, long term blank formed.

Aiming at this type of grim situation, what policies should China adopt? This is a question worthy of detailed study. The author believes that one should distinguish cases and begin development of work in 4 areas:

(1) With regard to beginning development of alkaline fuel cells, China still has a definite "residual power" (talent, technology foundation, and so on). This type of cell has already been recognized by the world at large (the U.S., Western Europe, possibly including the former Soviet Union) to be the best suited electric power source for manned spacecraft. As a result, one should quickly throw strength into taking alkaline power cell development and turning it into electric power

sources for manned spacecraft. This is not only necessary, it is also possible. There are people who believe, "At the present time, in aerospace planning, opting for the use of alkaline fuel cells is still not reliable." Although this point of view fits with reality in a way. However, if one delays and delays and does not begin study of this subject because of this, then, this is obviously short sighted and nonsensical. There is a need, at a minimum, to take alkaline fuel cells for aerospace uses and have them act as back up designs (secondary designs) in order to carry out support, striving, before the end of this century, to reach a level which can be of practical use. In conjunction with this, they should act as one starting point for reviving China's fuel cell development work.

(2) Outside China, phosphorous acid type fuel cells have already gone through test runs on power plants of levels from a few tens of kilowatts to ten megawatts. However, inside China, it is a total blank. Due to excessively great differences, it is estimated that independent development coming completely from China is already not worthwhile. It seems that current policy should be to strive to introduce from elsewhere small model prototypes (for example, 10-20kW) and gradually become familiar with the structure and operation of these systems as well as clearly determining the possibility of introducing these systems into practical use in China, and, going a step further, stipulate plans for the introduction of technology or the

introduction of commercial products with step by step implementation.

(3) Molten carbonate cells have developed rapidly outside China in recent years. However, they are still in a laboratory development phase. Looking at the long term, because of the fact this type of fuel cell has high electric generating efficiencies, it alone has a possibility of use as fuel cells associated with main electric generating stations. Due to relatively high operating temperatures, this type of cell also has relatively low requirements for fuel gas purity as a result. There is a possibility of indirectly using coal as fuel. This is relatively suited to China's national situation. At the present time, if China is capable of concentrating its strength, using an attack of approximately ten years on the key technical problems associated with 50-100kW MCFC power stations using coal as fuel, it is projected that, in the early part of the next century, the foundation will be laid for approaching the phase of practical utilization. Then, it is possible to strive to participate in the struggle associated with the practical utilization phase, in conjunction with this, very, very greatly strengthening China's position in the contention for conversion to practical use.

(4) Another trend which is currently worthy of attention should be polymer electrolyte membrane fuel cells. At the present time, this system is still not adequately mature. Development partakes greatly of the properties of the original models of test manufactured cells. In the various areas

of selection, improvement, and utilization of membranes and catalysts, in all cases, there are a number of operational musts. Besides this, due to the fact that initial phase development target powers were not large, as a result, expenditures were not high. Once there are breakthroughs, then, there are extensive application prospects in all areas such as military and civilian uses, small model power plants, transportation device power, and so on. It is possible to say that, at the present time, we are just entering into a good time for this field of development. We should decide promptly and opportunity, appropriately supporting the work of this area. It is possible to expect to relatively rapidly catch up to international levels in basic technology, taking a place in world development.

When carrying out the several fuel cell studies discussed above, if it is possible to strive for international cooperation or opportunities to introduce technology from elsewhere, this is undoubtedly beneficial for rapid development speeds. However, at the present time, outside China, this type of technology is seen, in all cases, as highly classified. It is estimated that there will be very few opportunities to realize this type of cooperation or introduction. (This point and the introduction of phosphorous acid cell prototypes are completely different.) As a result, there is a need to fix attention on being domestically based.

With regard to the suggestions above, I welcome colleagues and comrades charged with making science and technology policy to give criticism and correction.

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